
CHAPTER 2. LITERATURE REVIEW

2.1 Preface

In this chapter, a comprehensive review on the different aspects of rejuvenators are provided in section wise. The second section focuses on the changes in the composition of asphalt binder with aging and the requirements of rejuvenator. Different classifications available in the literature are highlighted in third section. In the fourth section, various parameters adopted for optimising the dosage of rejuvenators in the literature and their significance are underlined. In addition, the effects of the excess or less than required dosage application of rejuvenators on the rejuvenated binders are also highlighted. The fifth section provides the in-detail literature on the performance of rejuvenated recycled mixes. The sixth and final section covers the problem statement.

2.2 Requirements of a rejuvenator

To select a suitable rejuvenator, one should have a basic idea of the composition of the asphalt binder and the changes that takes place as it ages. It is mainly owing to the evidence that change in the binder's properties due to aging correlates well with its composition [70–72]. Also, pavements made from binders subjected to the same specification may differ in performance and serviceability. The main reason behind this variation is the difference in chemical composition (considering all other factors such as climate, traffic, design, etc.) [73]. In other words, two binders having the same grade may not have identical chemical composition, thus shows different behaviour when subjected to aging or when interacting with a modifier.

Asphalt binder is a colloidal or micelles system in which asphaltenes are dispersed and stabilized by the maltenes [74,75]. Maltenes are made of resins that are either aromatic or aromatic-naphthenic-aliphatic and an oily part that is aliphatic. Micelles comprise asphaltenes surrounded by a series of substances. Initially, in this series, substances close to asphaltenes

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are of high molecular weight and aromatic, followed by substances with low molecular weight and decreased aromaticity, and so on [76]. A binder's stability indicates the well-peptized asphaltenes (i.e., with enough resins surrounding them) without any flocculation or precipitation and mutual solubility and compatibility of the fractions [77,78]. In addition to the aromatic ring system, heteroatoms such as nitrogen, oxygen, sulphur, etc., imparts polarity and functionality to the asphalt binder. Their percentage varies from source to source, hence the variation in physical properties. Compatibility of the constituents and the resistance to aging are also related to chemical composition, affecting durability [79]. Chemical-physical interactions between the constituents of the binder governs the temperature dependent properties [80].

Binder can be either sol (exhibiting Newtonian behaviour), gel (exhibiting non-Newtonian behaviour), or sol-gel. Sol structure is observed when the asphaltenes are well peptized (micelles can move independently), and they majorly show viscous flow accompanied by minor initial elastic deformation and recovery. When there are not enough resins surrounding asphaltenes, micelles form bonds, resulting in an irregular open packing (clusters or aggregates) termed as gel structure. The binder then exhibits complex flow behaviour (elasticity, thixotropic, etc.) and displays age hardening. Generally, binders consist of a mixture of peptized asphaltenes and bonded/interconnected micelles resulting in a sol-gel structure that exhibits viscoelastic behaviour. The viscoelastic behaviour of the asphalt is defined by the micelles and their Brownian motion at suitably high temperatures [80–83].

Maltenes phase can also be broadly subdivided into nitrogen bases (polar compounds), first acidaffins (polar aromatics), second acidaffins (naphthenic aromatics), and paraffin's (saturates) [83]. A detailed description of the components is explained in Table 2-1. Colloidal stability index (CII), which is the ratio of the sum of asphaltenes and saturates to the sum of aromatics and resins, gives a better indication of the micelles' stability and dispersion binder.

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Lower the value better the colloidal stability, and hence it can be adapted to track the changes in binder due to aging and rejuvenation [84].

Table 2-1 Composition of asphalt binder [70,76,83,85–87]

Fraction	Description	Chemical reactivity	Roles
Asphaltenes (A)	<ul style="list-style-type: none"> • Solid, hard, and dark in colour • Higher molecular hydrocarbons (of aromatic nature) • Formed by condensation and dehydrogenation of aromatic-naphthenic (saturated cyclic) hydrocarbons • Insoluble in pentane (low-molecular aliphatic hydrocarbons) • Inert to air oxidation 	Very Low	<ul style="list-style-type: none"> • Bodying agent • Amount in asphalt depends on the viscosity of Maltenes • Imparts hardness and high melting point
Nitrogen bases (N)	<ul style="list-style-type: none"> • The resinous component containing all-nitrogen compounds (highly unsaturated) 	High	Strong peptizer for Asphaltenes

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	<ul style="list-style-type: none"> • Sensitive to oxygen and other elements • Precipitates with 85% H₂SO₄ 		
First acidaffins (A ₁)	<ul style="list-style-type: none"> • Unsaturated resinous hydrocarbons • Oxidize even under atmospheric conditions • Precipitates with concentrated H₂SO₄ (98%) 	High	Solvent for peptized Asphaltenes
Second acidaffins (A ₂)	<ul style="list-style-type: none"> • Slightly unsaturated or saturated hydrocarbons • Acts as transmissivity from resin to oily fraction • Precipitates with fuming H₂SO₄ (30% SO₃) 	Low	Solvent for peptized Asphaltenes
Paraffins (P)	<ul style="list-style-type: none"> • Oily component • Saturated hydrocarbons, including solid wax 	Low	<ul style="list-style-type: none"> • Gelling agent (dispersing phase) • Enhances the peptizing ability of N, A₁, A₂

Aging is mainly categorised into short-term aging, which occurs during production at elevated temperatures and long-term aging during the pavement's service life. Some of the mechanisms

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related to aging are - evaporation of volatile fractions, oxidation (forms polar chemical functional groups) due to the flow of air during mixing and in-service life, syneresis - which is the exudation of oils from asphalt to aggregates (due to limited peptizing resins) and is dependent on the chemistry of binder as well as the porosity of aggregates, time-dependent thixotropic property or steric hardening or molecular structuring, dissociation, isomerization, fragmentation, polymerization, photo-oxidation in case of the surface layers [70,79,83,88,89].

The oxidation rate mainly depends on the reactivity of the aromatic fractions [90]. Molecular microstructure and its physicochemical factors (dispersion, mobilization, and compatibility) also predominantly affect the kinetics of the aging in addition to the chemical reactivity of the constituents with oxygen [91]. Void content of the mixes, climatic conditions, and layer position in the pavement also influences the degree of aging [92]. Surface layers or mixes with high air void content will age comparatively higher than lower layers or mixes with low air voids [93,94]. Recycling processes such as stockpiling and multiple heating also result in further oxidation of aged binder [95].

Due to aging, certain portions of the maltenes phase convert into the asphaltenes phase, resulting in the maltenes phase with reduced solvent power and increased asphaltenes [96]. Aromatics fraction decreases among the maltenes phase as they convert into resins and then finally into asphaltenes. Due to its low reactivity, the saturates portion remains the same. Incompatibility arises as the ratio of maltenes to asphaltenes decreases due to aging, and the binder becomes brittle and dry [90,97–99]. Oxidation also results in the formation of carbonyls (ketones, carboxylic acid, anhydrides) and sulfoxides, due to which the polarity and stability of the asphaltenes get enhanced [91,99,100]. Carbonyls are formed in the aromatics, resins and asphaltenes, whereas sulfoxides are formed in the resins and asphaltenes [101]. Binder's susceptibility to aging can be indicated by the compositional parameter (rostler parameter)

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$(N+A_1)/(P+A_2)$, which is the ratio of high reactive to low reactive compounds [85,92]. The ratio of nitrogen bases to paraffins (N/P) indicates the binder liability to the syneresis [85,102].

The solubility parameter of the maltenes phase also affects the viscosity (since the degree of aggregation of asphaltenes varies) along with the oxidation; higher solvency lowers the viscosity [99,103]. Some binders can be oxidized, but the increase in viscosity would be less if the maltenes phase had high solubility. Sulatana and Bhasin [104] concluded that increased polar fractions (i.e., aging) affect stiffness predominantly at high temperatures or low loading rates while retaining the properties at low temperatures or high rates of loading. It should be highlighted that aging increases the stiffness of imparting constituents and enhances the stiffness of each fraction [105].

Considering the effect of the aging, rejuvenator should be such that the solvency power of the maltenes increases and asphaltenes be well dispersed by restoring the maltenes to asphaltenes ratio. This can be achieved by having high polar compounds and aromatic contents, minimum of 9 and 60%, respectively [96]. High aromatic contents also improve the temperature and hardening susceptibility of the binder [90]. But there are some emission problems associated with high aromatic contents. Additionally, consistency is negatively affected due to high aromatic percentages [106]. As aging increases asphalt's viscosity due to amplified asphaltenes content, the amount of asphaltenes fraction in the rejuvenator should be kept as low as possible [98]. Since saturates amount was unaffected by aging, it was recommended that the rejuvenator have not more than 30% of the saturates [107]. It was observed that saturates are associated with the binder's hardening susceptibility, and high saturates would result in cracking of the pavement [98]. Waxes that are part of saturates affect the low-temperature properties and should be avoided [90].

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It should be noted that the components that reduce the viscosity may not be effective in enhancing the durability and stability of the asphalt binder, i.e., solely increasing saturates (oily part) may reduce the viscosity, but it does not guarantee in bringing back the balance [77]. Therefore, rejuvenators should work by diluting the aged binder (i.e. increasing maltenes phase) and dissolving asphaltenes (breaking agglomerations into small sizes). The ratio of the aged viscosity to the original viscosity less than three and the percentage of weight loss after rolling thin film oven test less than four were proposed for the durability aspect [35,107].

Pahlavan et al. [108] synthesized a bio rejuvenator from the swine manure and algae, which was highly effective in breaking the clusters of asphaltenes and restoring the colloidal balance that helped in increasing the crossover modulus and crossover frequency. This study can be an example to highlight the importance of considering the rejuvenator's chemical composition and compatibility. With due consideration of all these aspects, a compatible rejuvenator that restores the asphalt's chemical constituents should be selected so that syneresis does not occur (by adding peptizing resins) and regains elasticity (oily component). Change in the composition of the binder due to aging and rejuvenation is presented in Figure 2-1.

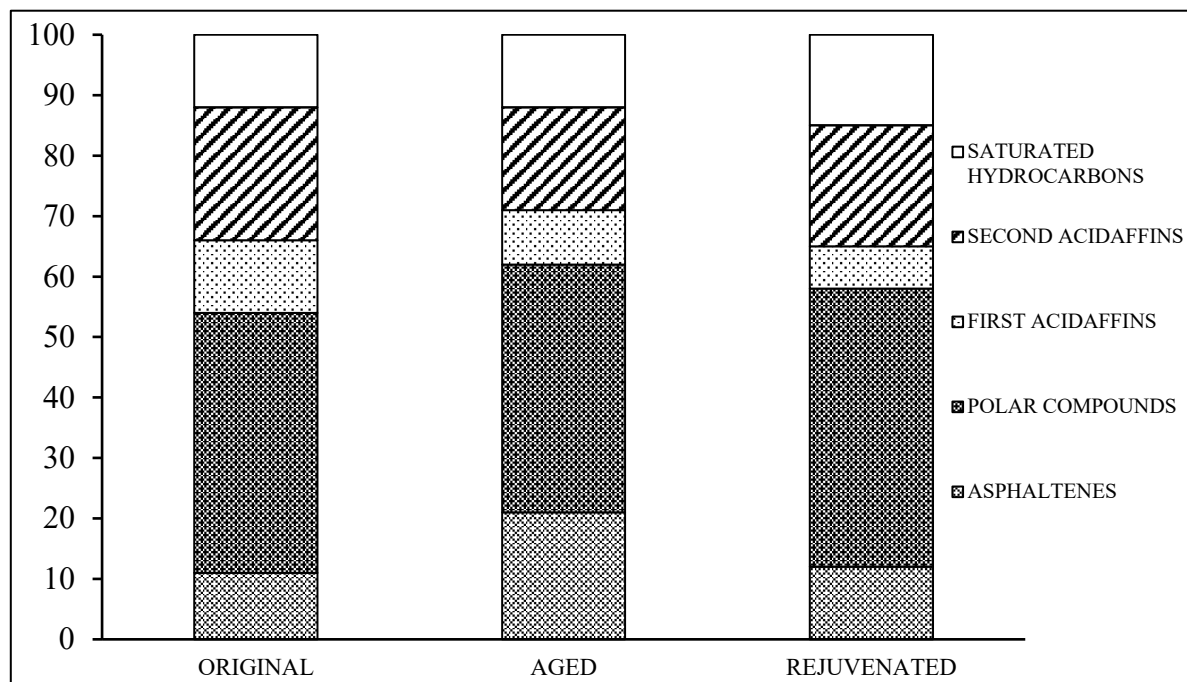


Figure 2-1 Change in the composition of the binder with aging and rejuvenation – recreated from [109] (values are approximate)

2.3 Classification

Different types of classification of rejuvenators are as follows:

- Depending on the source
 - a. Petroleum-based
 - b. Organic-based
 - c. Commercial rejuvenators (can be of organic type or petroleum type).

Petroleum-based rejuvenators are rich in maltenes and restore the maltenes-asphaltenes ratio.

In contrast, organic-based rejuvenators restore aged binders by using an agricultural medium (an agricultural product of unknown composition transfers necessary fractions) [110]. Most of the petroleum and organic based rejuvenators are waste-type or recycled products and therefore, can be roughly categorise them as waste-type (recycled) rejuvenators (WR).

Commercial rejuvenators (CR) are engineered products manufactured to resemble the maltenes

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portion of asphalt binder. Essential ingredients for CR can be either bio-oil-based or petroleum-based. There can even be some additional components intended for specific purposes such as enhancing moisture or aging resistance etc. WR, being a re-used product, has an economic advantage over CR. However, the process of collection, maintaining uniformity (in terms of source), processing (required in some cases), and then integrating it into the HMA can be challenging. Various products that are adopted in various studies are shown in Table 2-2.

Table 2-2 Classification of rejuvenators based on the source

Petroleum based	Organic based	Commercial
➤ Aromatic extract	➤ Organic oil	➤ Cyclogen® L
➤ Paraffinic base oil	➤ Refined tallow	➤ Reclamite
➤ Naphthenic flux oil	➤ Distilled tall oil	➤ Revive™
➤ Petroleum tech oil	➤ Waste vegetable oil	➤ Sasol orbital plus
➤ Waste engine oil	➤ Waste vegetable oil	➤ ANOVA
➤ Waste engine oil bottom	grease	➤ Green-Tech
➤ Aromatic oil	➤ Waste vegetable oil	➤ Agriculture-Tech
➤ Cereclor (Chlorinated paraffin)	refined	➤ Nynas V115
	➤ Castor oil	➤ Wood tar based
	➤ Pongamia oil	
	➤ Waste pig fat based	
	➤ Polanga oil	
	➤ Soybean oil derivatives	
	○ Epoxidised methyl soyate	

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	<ul style="list-style-type: none"> ○ Sub epoxidised soyabean oil ➤ HR-1, HR-U and FU 	
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- ASTM D4452 and IS 17052 classification

Based on the values of physical properties of rejuvenator such as viscosity at 140°F, flash point, saturates, specific gravity, viscosity ratio and weight change after short-term aging, American Society for Testing and Materials (ASTM) D4452 classified rejuvenators as shown in Table 2-3 and Indian Standard (IS) 17052 classified rejuvenators as shown in Table 2-4. Compared to ASTM, IS considers only three types of rejuvenators and very stringent on the weight change after RTFO or TFO test. Comparing RA 25 from both the classifications, it can be seen that IS classification considers softer rejuvenators with higher stability (less weight change).

Table 2-3 Classification as per ASTM D4452

	Viscosity at 140°F, cSt	Flahs point, F (minimum)	Saturates, wt % (maximum)	Viscosity ratio (maximum)	Weight change, %
RA 1	50-175	425	30	3	4
RA 5	176-900	425	30	3	4
RA 25	901-4500	425	30	3	3
RA 75	4501-12500	425	30	3	3
RA 250	12501-37500	425	30	3	3
RA 500	37501-60000	425	30	3	3

Table 2-4 Classification as per IS 17052

	Viscosity at 60°C, cSt	Flash point, °C (minimum)	Saturates, wt % (maximum)	Viscosity ratio (maximum)	Weight change, %
RA 25	250-1000	220	30	3	0.5
RA 100	1004-4000	220	30	3	0.5
RA 400	4001-16000	220	30	3	0.5

- National Centre for Asphalt Technology (NCAT) classification

Categorised into [111]

- Paraffinic oils: (refined used lubricating oils) such as waste engine oil, waste engine oil bottoms etc.,
- Aromatic extracts: (refined crude oil products) such as Hydrolene, cyclogen, etc.,
- Naphthenic oils: (engineered hydrocarbons) such as SonneWarmix, etc.,
- Triglycerides and fatty acids: (vegetable oils) such as waste vegetable oil, oleic acid, etc., and
- Tall oils: (paper industry by-products) such as Hydro green etc.

- Hassan and Todd classification [84]

Based on how rejuvenators modify the compositions of the aged binder:

- Soluble softeners - increases maltenes phase
- Compatibilisers - reduces viscosity and also breaks agglomerations of asphaltenes into small sizes and
- Incompatible softeners – products with high saturates that reduces viscosity but induces colloidal instability and asphaltenes precipitation

2.4 Tracking and optimising rejuvenators

One of the most critical aspect of rejuvenators is optimising the dosage. It should be kept in mind that any rejuvenator can successfully restore aged binder properties at a specific (optimised) dosage. But using a very high dosage may affect the optimum binder content and reduce the cohesion and adhesion properties, increasing moisture susceptibility and pavement deformation. Besides, flushing, i.e., oils migrating to the surface, may also severely affect pavement performance due to reduced friction [32,69]. On the other hand, a low dosage does not confirm rejuvenation. So dosage has to be selected cautiously, and to be safe, choosing rejuvenators with viscosity as low as possible is better. Dosage should be selected to increase mixture resistance to cracking while maintaining the rutting potential [112]. Hence the effectiveness of a rejuvenator can be realized from its optimum dosage. It was also reported that a single optimum dosage of rejuvenator can restore the rheological properties at any blending ratio of RAP and virgin binder (which need not be true in all cases) [113].

The typical procedure to evaluate dosage is to mix the recycling agent with the extracted RAP binder at different percentages until it attains desired consistency. Pellet abrasion test, penetration at 25°C, viscosity at 60°C, ductility test, softening point test (Ring & ball test), and performance grade (PG) grade using dynamic shear rheometer (DSR) are some of the tests used for evaluating the dosage [51,62,86,97]. Performance tests can also be used to validate or estimate the amount of rejuvenator such that the results are comparable to the conventional mixtures (having no RAP) [59]. Sometimes a rejuvenator or its dosage obtained by a single test (penetration or viscosity or PG, etc.) may not restore every property (fatigue, rutting, moisture, etc.). In that case, additional additives may help improve that specific aspect, for example, using antistripping agents in case of moisture susceptibility [58].

An exponential increase in penetration with a high content of rejuvenator was observed [67,114]. Conversely, a linear relation was also reported [115,116]. Critical temperatures

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determined while evaluating the performance grade were also based on the mixing rules. The binder's performance grade also varies linearly with the change in dosage of the rejuvenator [112,114]. Farhad et al. [117] performed tests to evaluate the best suitable parameters that explain the chemical changes due to oxidative aging and established that dynamic shear modulus (at 64°C and 10 rad/s) and Glover-Rowe parameter (an indicator of ductility) correlate well. Therefore, these two rheological parameters can indicate the effectiveness of rejuvenators on reconstituting the chemical composition. Garcia et al. [118] also concluded that rheological characterization (low and high-temperature PG and Glover-Rowe parameter) gives a better idea of rejuvenation. It was observed that the efficiency of the rejuvenator decreases after long-term aging, and it pointed out that aged properties for rejuvenated blends should also be evaluated. An aged binder after rejuvenation behaves analogously to a virgin binder or sometimes inferior (ages rapidly) than a virgin binder and has to be evaluated accordingly. Similar conclusions were also reported by other researchers [66,113].

A better approach for evaluating a suitable rejuvenator (type and dosage) would be assessing the performance of both binders and mixes [49]. Nahar et al. [119] assessed the effect of two rejuvenators (BM1 and CM1) on the rheology and microstructure. From rheological results, it was observed that CM1, at 10%, softens the aged binder more than BM1 at 20%. However, from the microstructural (phase) images obtained using AFM, as shown in Figure 2-2, the addition of BM1(20%) modifies the structure of aged binder similar to virgin binder (desirable), but CM1 (10% and 25%) had entirely different influence. Yu et al. [120] also characterized the rejuvenating effect using rheology, microscopic and chemical methods. Results suggested that rejuvenation depends on the rejuvenator, binder source, and combination. Hence, the rejuvenation mechanism differs from one rejuvenator to another. It is better to conduct (if possible) physical, rheological, chemical, microstructural, thermal analysis etc. tests on the rejuvenated binder to have a complete understanding.

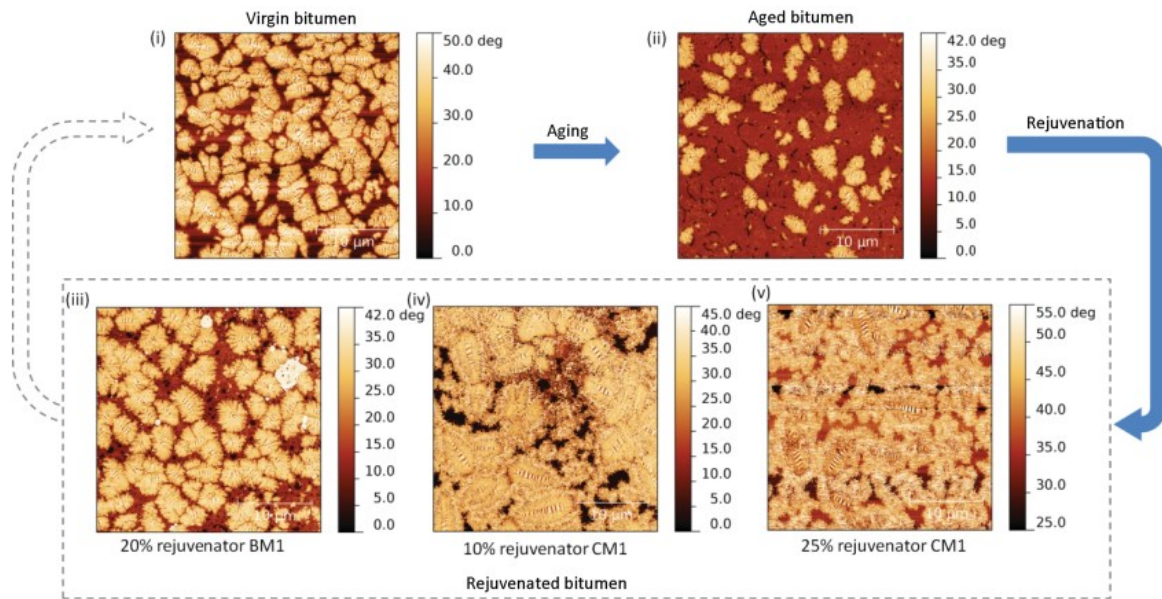


Figure 2-2 Microstructural images of binder after aging and rejuvenation [119]

It should be highlighted that rejuvenator does not instantly combine with the aged binder coated over the RAP aggregates. In addition to the mechanical blending that happens during mixing, the diffusion mechanism that takes place over a certain period helps the rejuvenator to mix and soften the RAP binder. The effect of the dosage of proper rejuvenator and its diffusion on the asphalt binder structure is depicted in Figure 2-3. Despite proper mixing, if diffusion is slow, resultant mix properties cannot be adequately predicted since the stiffness of the mix varies with time due to continuous diffusion [121].

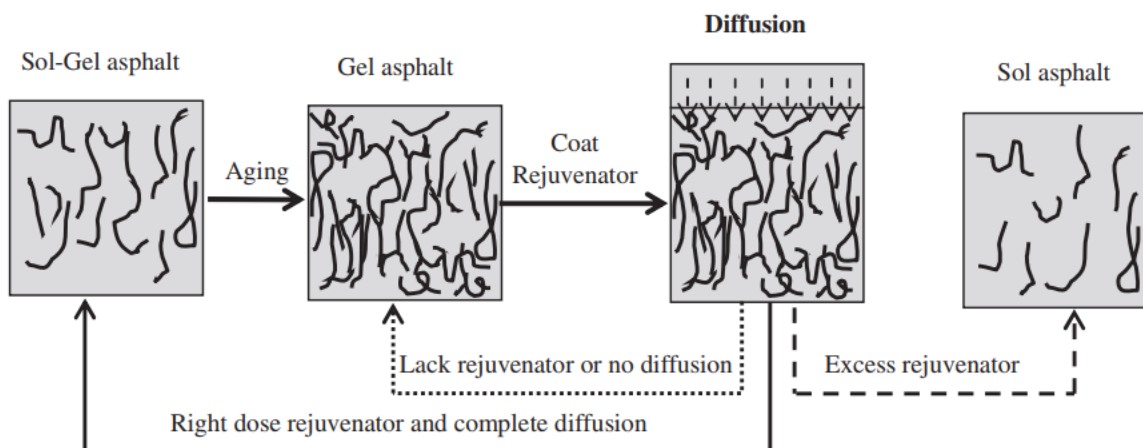


Figure 2-3 Influence of dosage and diffusion on the asphalt binder structure [122]

2.5 Performance of rejuvenated recycled mixes

The designed mix must be able to endure the harsh conditions of the climate and traffic; hence, assessing the impact of the RAP on the performance gives the notion of its behaviour in the field. It should be noted that depending on the climatic conditions, traffic loading (mode, magnitude, frequency and rest period), pavement structure (layer and foundation), properties of mixes, surface and sub-surface drainage, and the mutual effect of all these parameters, the expected performance of the recycled mixes in field can vary (either positively or negatively) from what they were designed for in the laboratory. Therefore, unknown origin, properties and age must not be the factors for excluding RAP [123].

2.5.1 Fatigue resistance

The effect of different rejuvenators on the cracking resistance of recycled mixes with different percentages of RAP is illustrated in Table 2-5. In most of the cases, fatigue performance improved due to the rejuvenators. In some cases, when rejuvenators are added fatigue resistance of recycled mixes may have improved, but still not comparable with virgin mix. Reasons for the decreased fatigue performance observed in some studies are: rejuvenators aging susceptibility [61], different blending level of recycled asphalt and distribution [63],

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attributed to the parameter used, fatigue performance decreased in terms of fracture energy but fracture index increased [124], [125]

Table 2-5 Factors affecting the fatigue performance of rejuvenated recycled mixes

Rejuvenator	RAP %	Test	Fatigue resistance	Remark	
Aromatic oil	15%	Illinois flexibility index test	Increased with dosage	The rate of increment was high, between 0 and 3% and decreased when the dosage was increased from 6 to 9%	[126]
R1, R2, R3	19%	Overlay test	Increased	Rejuvenator (R3) added directly to RAP showed improvement	[127]
Modified alkyl polyamine rejuvenator	20%	Four-point bending test	Increased	A small dose of 1% improved the cumulative dissipated energy	[55]
Crude tall oil	25%	Four-point bending test	Increased	Enhanced performance at	[123]

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				both unaged and LTA conditions	
Soft virgin binder (160/220), Rheofalt HP-EM and storflux nature	20% and 40%	Cylindrical indirect tensile test (stress controlled)	Increased (except for 20% with storflux nature)	-	[128]
Sub-epoxidized soybean oil	40% (fine)	Four-point bending test	Increased	Polymer-modified PG 58-34 was used	[129]
Base oil (and soft binder 80/100)	10, 30 and 50%	Indirect Tensile Fatigue Test	Increased	Increased for both 20 mm wearing course and 28 mm base course	[53]
A, B, C	50%	Four-point bending test	Increased	Interfacial blending zone bonding energy influenced the fatigue performance	[50]
WCO, Rapiol, Cyclogen	50%	Indirect tensile fatigue test	Increased fatigue life at unaged but	Aging (STA and LTA) decreased performance	[61]

			decreased at STA and LTA	(biggest change for WCO)	
WVO and commercial rejuvenator	50%	Semi-circular bending	FE decreased, but FI increased	8% commercial rejuvenator had the same performance as 14% WVO	[124]
RA1, RA2 and RA3	30, 40 and 50%	Four-point bending test	Decreased (compared to control mix)	Performance varied depending on the test temperature, loading mode and testing periods	[63]
Tall oil, triglyceride, WVO and tallow oil (and VG 10)	60%	Indirect tensile fatigue test	Increased	-	[130]
R2 and R3	40 and 60%	Two-point bending test	Decreased	R3 (high viscous) had more rejuvenating efficiency at 40%, while R2	[125]

				(low viscous) with 60%	
Wastewater treatment sludge (WTS)	40 and 60%	Semi-circular bending	Decreased (from FI)	The effectiveness of WTS improved with the increase in RAP %	[52]
Vegetable oil, WEO, composite rejuvenator	60% (fractionated)	Four-point bending test	Decreased (compared to control mix)	WEO had the lowest fatigue life	[57]
R1, R2 and R3	65%	Semi-circular bending	Increased	Though there is no obvious difference in FE, FI differentiated cracking resistance	[54]
Crude tall oil	75% (fractionated)	Four-point bending test	Increased	Aging decreased fatigue resistance highly for recycled mixes	[131]
WVO (and VG 10)	60 and 90% (fractionated)	Indirect tensile fatigue test	Increased by 60% and decreased by 90%	Only 60% recycled mix with rejuvenator had a fatigue life	[132]

				higher than the control virgin mix	
Soy oil and WCO	70% (I 29) 84.5 and 83.5 % (H32)	Semi-circular bending	Decreased	-	[133]
ACF and motor oil	100%	Four-point bending test	Increased (with and without rejuvenator)	High binder content, low viscosity, high fines and strong bond increased performance	[62]
Cyclogen and Rapiol	25, 50, 75 and 100%	Indirect tensile fatigue test	Increased at 25% and then decreased	Cyclogen performed better than Rapiol	[134]

2.5.2 Rutting resistance

The percentage reduction of rutting resistance for rejuvenated recycled mixes compared with mixes without rejuvenators is shown in Figure 2-4. With the increase in the degree of blending, RAP binder gets converted to free binder, increasing VMA and apparent film thickness. Excess rejuvenator content increases the softer free binder, resulting in reduced high-temperature performance. Some studies indicated that rejuvenators reduce the rutting resistance of recycled mixes at different RAP percentages but performed better than the control virgin mix, as shown in Figure 2-5. It demonstrates that the impact of RAP was more than softening effect of the rejuvenator [57–63,134]. It can be attributed to the rejuvenator's dosage optimisation method

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and parameter. Good rutting performance can be obtained if the rejuvenator dosage is evaluated using softening point or viscosity at 60°C [130,132].

The efficacy of rejuvenators depends on the percentage and size of RAP and the addition method. Rejuvenators (R1 and R2) added to the virgin binder at their recommended dosages did not influence the rutting considerably (marginally decreased rut depth) for 9.5 mm mixes with 19% RAP. R3 rejuvenator added to RAP slightly increased the rutting potential [127]. Using 2% base oil with 30% RAP slightly improved the rut resistance, but 8% base oil with 50% RAP again negatively affected the performance [53]. The addition of 40% RAP increased the dynamic stability by 7%, while 70% of RAP improved the dynamic stability to 2.3 times for 19 mm mixes with 7.9% commercial rejuvenator and 60/80 binder [135]. When 8% (by weight of virgin binder) sub-epoxidized soybean oil rejuvenator was added to 9.5 mm recycled mixes with 40% fine RAP and PMB PG 58-34 E+, the increase in rut depth was marginal [129].

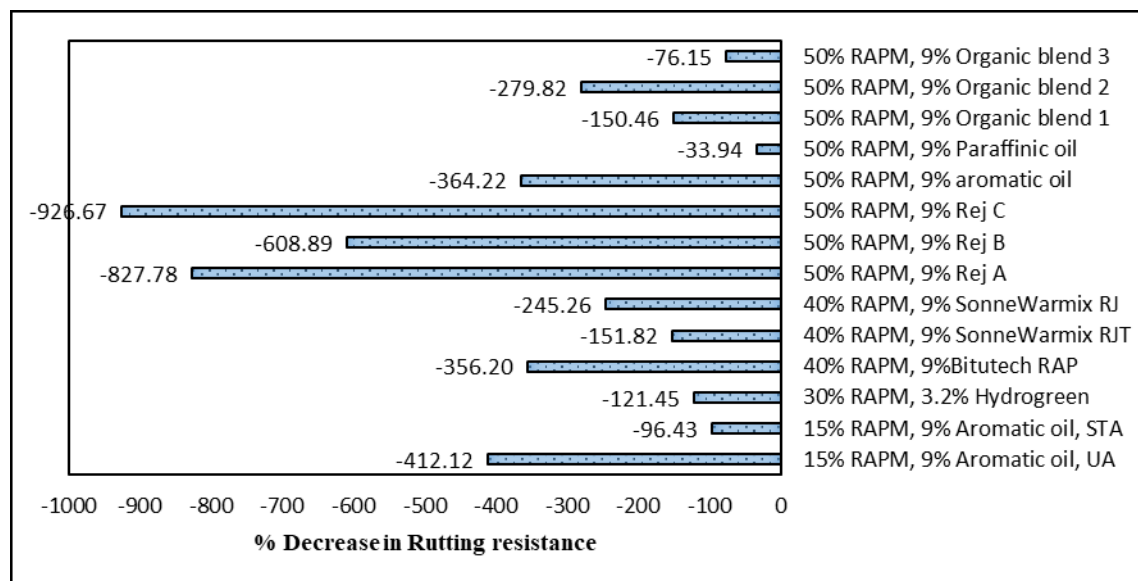


Figure 2-4 Effect of rejuvenators on rutting [50,64,126,136,137]

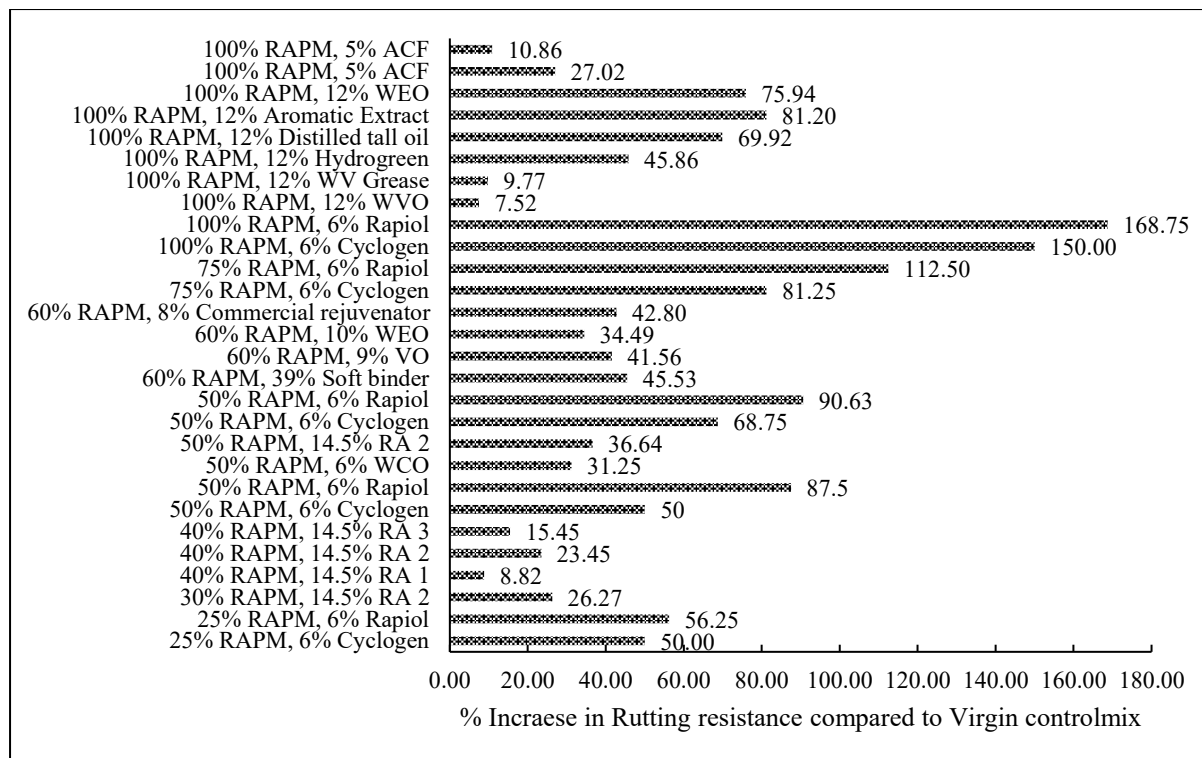


Figure 2-5 Rutting resistance of rejuvenated mixes compared to virgin mix

[57,58,60,62,63,134]

Table 2-6 shows the rejuvenator having better rutting resistance among different rejuvenators. These studies highlighted the importance of the composition of rejuvenators on the performance of recycled mixes.

Table 2-6 Better performing rejuvenators (type) in rutting

Rejuvenators	RAP %	Binder	NMAS	Test	Better performing rejuvenator type	
WEO, commercial waste oil, tallow oil, WVO, tall oil	60%	VG 10	19 mm	Wheel track tester	Paraffinic oil-type rejuvenators	[130]

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					(WEO and commercial waste oil)	
aromatic extract, green tech (tall oil), agriculture tech-based (soybean oil)	65%	PG 64-34	12.6 mm	Dynamic creep	agriculture tech-based (soybean oil)	[54]
RA 1 (31% saturates, 49% aromatics and 15% resins), RA 2 (60% saturates, 20% aromatics and 9% resins), RA3 (40% RA 1 and 60% RA 2)	40%	70 pen	19 mm	Wheel tracking rut test	RA 2	[63]
RA2 (aromatic oil, plasticizer, and antistripping agent in the ratio 100:10:2 and 20% 110 pg), RA 3 (same 100:10:2 but 30% 110 pen)	40 and 60%	60/80	19 mm	Wheel tracking test and Hamburg wheel tracking test	RA 3	[125]

Rejuvenators effect on the rutting changes after aging. Espinoza-Luque et al. [126] found that rejuvenator's influence on the rutting potential was only prominent at high dosages (9%) after short-term aging. Similarly, Antunes et al. [131] also reported that virgin mixes were more

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affected by aging to a great extent than recycled ones. However, Ziari et al. [61] concluded rejuvenators had the highest increase in flow number after LTA.

Soft binder (160/220) had better deformation resistance than rejuvenators (Rheofalt HP-EM and Storflux Nature) when used with 20 and 40% recycled mixes having 11 mm NMA5 and 50/70 virgin binder. However, with the increase in RAP percentage (20 to 40%) the difference in the performance between soft binders and rejuvenators decreased [128]. For 60% recycled mixes with 70 dmm virgin binder, soft binder (160 dmm) had the highest DS value, followed by composite rejuvenators, vegetable oil and WEO [57]. Therefore, a soft binder was also found to be an effective rejuvenating agent and perform comparable to or even better than rejuvenators.

2.5.3 Moisture resistance

Interface cohesion between aged RAP binder and aggregate increases due to the addition of a rejuvenator resulting in enhanced moisture resistance. The performance of rejuvenators depends on the blending level and distribution of RAP and virgin mix [63]. Modified alkyl polyamine rejuvenator reduced the viscosity of the binder and enhanced the coating. Rejuvenator increases moisture resistance and reduces the deterioration caused by other distresses such as rutting, fatigue and low-temperature resistance due to moisture [55]. From indirect stiffness modulus ratio (ratio of stiffness modulus after conditioning to before conditioning), 28 mm base course and 20 mm surface course recycled mixes with 10, 20 and 30% RAP and base oil rejuvenator were not susceptible to moisture even after three cycles of conditioning [53]. Tensile Strength Ratio (TSR) values increased with an increase in degree of blending and decreased with an increase in RAP. If moisture resistance were safe at the design stage, there would be no risk after construction. Variation of degree of blending influenced TSR values more at high RAP contents. Free binder content and its properties affect the

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performance to a great extent [138]. Rejuvenator dosage was an essential factor in controlling moisture resistance and depended on the percentage of RAP [139].

In the case of moisture resistance, the type of virgin aggregates also plays an important role and controls the effectiveness of soft binders and rejuvenators for recycled mixes. Shen et al. [140] evaluated the moisture resistance of 9.5 mm mixes with two types of virgin aggregates (granite and gneiss), different percentages (0, 15, 38 and 48%) of fractionated RAP, and two types of rejuvenators (soft virgin binder and oil type). For granite, soft virgin binder had low ITS values than the control mix, but oil-type rejuvenators had ITS values at all percentages of RAP. For gneiss, soft binder and oil type rejuvenator had higher ITS than the control mix.

2.5.4 Modulus

As rejuvenators reduce the stiffness imparted by the aged RAP binder, modulus is likely to decrease. 40% RAP increased dynamic modulus, but rejuvenators (BituTech RAP, SonneWarmix RJT and SonneWarmix RJ) decreased the values [64]. Rejuvenators (ACF and used motor oil) decreased stiffness modulus for 100% recycled mixes [62]. 65% recycled mixes with rejuvenators (petroleum-based, green tech-based, agriculture tech based) had low modulus than the control virgin mix [54]. Increasing the dosage of commercial rejuvenator and penetration grade of virgin binder decreased the modulus, while using additive increased the dynamic modulus [141].

The effect of rejuvenators varies depending on the test temperature or frequency also. 25% fractionated RAP, and crude oil rejuvenator slightly decreased stiffness modulus (at higher frequencies) and aging increased stiffness (mainly at lower frequencies) [123]. Compared to control mix (18% RAP and PG 58-28S), mix with 30% RAP and Epoxidized methyl soyate rejuvenator had low dynamic modulus at intermediate temperature or frequencies of E^{-06} to E^{-04} Hz. But at high and low temperatures, both mixes had similar modulus [142]. Rejuvenators

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(R1, R2, R3) decreased dynamic modulus only at high temperatures of 40°C (but not at 4 and 20°C) [127]. Oleic Imidazoline and Rapeseed Imidazoline rejuvenators decreased stiffness modulus at 23, 10 and -2°C [143].

However, some studies observed that rejuvenated recycled mixes had higher stiffness than virgin mixes. 40 and 60% recycled mixes with rejuvenators (R2 and R3) had high stiffness than the control virgin mix [125]. 60% fractionated RAP with rejuvenators (soft binder, vegetable oil, WEO and composite rejuvenator) had dynamic modulus higher than control virgin mix [57]. For 20% recycled mixes, using soft virgin binder (160/220) and Rheofalt rejuvenators resulted in stiffness (cylindrical indirect tensile test) similar to or slightly higher than the control virgin mix with 11 mm NMAS and 50/70. But storflux with 20% RAP, Rheofalt and storflux with 40% RAP had stiffness lower than the control mix [128]. Although rejuvenators (Cyclogen, Rapiol, WCO) decreased modulus by 16 to 33%, values were still more than the virgin mix. Aging also increased modulus, comparatively higher for rejuvenated recycled mixes than virgin ones [60,61]. At different percentages of RAP (0 to 100%), rejuvenators (Rapiol and cyclogen) had higher resilient modulus values than virgin mixes [134]. Thus the restoration of viscoelastic behaviour depends on both percentages of RAP and the type (composition, viscosity and dosage) of the rejuvenator.

2.6 Problem statement

Considering the environmental and economic advantages, the application or usage of RAP in the flexible pavements is growing continuously throughout the world. Rejuvenators provide a reliable solution to the negative aspects connected to the stiff binder of RAP and thus are generally used to accommodate high contents of RAP in hot mix asphalt recycling. Literature review related to various aspects such as composition of rejuvenators considering the changes that takes places in the asphalt binder due to aging, parameters or tests for evaluating the dosage, performance of recycled mixes and challenges associated with the filed RAP are

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elaborated in this chapter. However, despite of the extensive work done on the rejuvenators there are some aspects that still needs to be studied to inflict confidence and maximize their applicability by means of effective approaches. In this regard, following aspects need to be studied further:

- Although different parameters are proposed to effectively evaluate the optimum dosage of rejuvenators, a reliable parameter that would result in the balanced performance considering the variables such as rejuvenator type and RAP percentages is yet to be standardized.
- Selection of a rejuvenator (based on the properties of a rejuvenator) among several varieties of rejuvenators that would result in satisfactory performance of recycled mixes not depending upon the rejuvenator type and amount of RAP to be used, is not explored in the literature commendably.
- Durability is one of the most important aspect of any new or existing technology that controls its effectiveness and applicability. In case of rejuvenators, durability based on the performance of recycled mixes would be a better approach to decide the most effective rejuvenator.
- Variation in the source is an important factor that can influence its applicability while recycling a waste material. Waste engine oil is one of the promising rejuvenator available, but the effect of source is not yet studied in the literature.